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Review of design conditions applicable to offshore wind energy systems in the United States

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Abstract

Offshore wind turbines are now being considered for use in the United States. Ensuring proper design of offshore wind turbines and wind farms requires knowledge of the external conditions in which the turbines and associated facilities are to operate. The primary external conditions are due to the wind and waves. Also, for many locations, floating ice will also be a major factor in the design. This review examines the following aspects of external conditions for the design of offshore wind turbines for the United States: (1) design requirements, (2) available offshore data sources, (3) data estimation and extrapolation techniques, (4) on-site data collection, and (5) likely sources of extreme events, including hurricanes and northeast storms.

Keywords: Offshore wind; Wind turbine design; Offshore wind systems data

Contents

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1. Introduction

Windturbines, whether intended for use on land or offshore, must be designed for a range of conditions. Some conditions will correspond to normal operation, where most of the energy will be produced. Others are extreme or unusual conditions. In the design process, conditions are sought such that, if the turbine can meet those conditions, it will perform at least adequately under any other realistic set of conditions. The most important considerations are: (1) expected events during normal operation, (2) extreme events, and (3) fatigue.

The design of offshore turbines has many similarities to those of land based turbines, but there are a number of differences as well as additional considerations. Work is now underway to develop offshore wind turbine standards. Europe has led the world in offshore wind turbine research and, as a result most of the development to date has occurred there, primarily in the Baltic and North Seas. Much of this work will be applicable in the US as well, but there are some conditions that may require special attention. For example, one question that occasionally arises is how applicable offshore turbines designed for northern European conditions are to North America, where among other things, hurricanes occur relatively frequently.

External conditions refer to events that take place in the environment of the wind turbine, which can have a significant impact on the operation or the structure of the wind the turbine. For offshore wind turbines the most important external conditions are those associated with wind and waves. In cold climates, floating ice may also be a significant external condition. Sea currents, storm surges, and tidal variations may also be important in the design of offshore foundations, but they are not discussed in this paper.

Nomenclature

Lower case roman

c	Weibull scale factor for wind speed distributions
d	water depth
f	frequency in Hz
f_{p}	frequency at the spectral peak
g	acceleration of gravity
h	reference wave height
k	Weibull shape factor for wind speed distributions, wave number $= 2\pi/\lambda$
p	probability density function
r	lag number, radius
s	distance in the direction of travel $= x\cos(\vartheta) + y\sin(\vartheta)$
t	time
u	instantaneous wind speed, particle velocity
$\tilde{u}$	wind speed fluctuations
u'	gust factor
u^*	friction velocity
x,y	perpendicular axes in plane of ocean surface
z	wave height axis, with z positive above still water level

Upper case roman

A	numerical parameter used in Pierson–Moskowitz spectrum, a function
B	numerical parameter used in Pierson–Moskowitz spectrum
C	normalizing constant used in JONSWAP spectrum
C_{D}	drag coefficient
C_{M}	inertial coefficient
D	diameter
$D(z)$	depth decal function $= \cosh[k(z + \mathrm{d})]/\cosh(kd)$
$D(\vartheta, f)$	wave direction distribution
E	spectrally integrated energy of the waves
$E(\vartheta, f)$	wave direction spectrum
F	cumulative density function
$\tilde{F}$	force per unit length
H	wave height
H_0	mean significant wave height
H_{c}	Weibull scale factor for wave height distributions
H_{s}	significant wave height
$\hat{H}$	wave amplitude
I_{t}	turbulence intensity
L	integral length scale of the turbulence
N	number of long term samples, recurrence period
N_{s}	number of samples
R	radius to maximum wind

$R(r\delta t)$	autocorrelation
S	source function
S_H	wave height power spectral density
S_u	wind speed power spectral density
T	wave period
T_1	averaging period of the mean wind speed
T_2	gust averaging period
T_{p}	peak period
T_{z}	zero-crossing (or mean) period
V_{fm}	velocity of forward motion
V_{g}	unit vector in the direction of the wave group velocity
U	mean wind speed
$\bar{U}$	long-term mean wind speed
X	fetch length

Greek

γ	Weibull shape factor for wave height distributions
ϑ	direction of wave relative to x-axis
λ	wave length
σ	numerical parameter used in JONSWAP spectrum
σ_H	standard deviation of wave height
σ_u	standard deviation of wind speed
σ_U	long-term wind speed standard deviation
ω	frequency $= 2\pi/T$ in radians/sec
$\int$	product operator
Φ	velocity potential

Subscripts

i	ith in a summation
ij	index of particular sea state
max	maximum

The process of incorporating loads into the design process consists of the following:

- determine a range of design external conditions;
- specify design load cases of interest, including ones during operating and extreme conditions;
- calculate the loads for the load cases;
- verify that the stresses due to the loads are acceptable, considering suitable safety factors.

2. Scope of review

This paper reviews a number of the aspects of external conditions for the design of offshore wind systems for the US. First, it describes how and why external conditions

are important to the design of offshore wind turbines. Much of this information is included in present design standards, including those developed by Germanischer Lloyd [1] and being developed by the International Electrotechnical Commission (IEC) [2]. Of particular importance to standards development are descriptions of the external conditions in such terms as short term means, turbulence intensities, extreme events, probability density functions, and spectra. Second, the paper describes offshore data that are commonly available in the United States. Third, when real data are only available for the general vicinity of a prospective offshore wind installation, it may be of interest to use extrapolation techniques such as hindcasting or measure-correlate-predict (MCP). The applicability of such techniques will be considered. Fourth, for new sites, it is presumed that some on-site data collection will be needed. The type of data collection to be undertaken at offshore wind sites will be reviewed. Fifth, brief descriptions of major sources of extreme weather events will be given.

3. Design requirements of offshore turbines

Offshore turbines are those whose foundation may be subjected to hydrodynamic loading. To date, all offshore wind turbines have been installed on stationary foundations, located on the ocean floor, in water less than 20 m deep. While all existing offshore wind turbines have been installed in Europe, a number of projects have been proposed recently for the coastal waters of the US. A typical offshore turbine is shown in Fig. 1 [3]. Kuhn [4] notes that there are two approaches followed for offshore wind turbines: (1) marinisation of robust and proven onshore designs, and (2) more radical designs that consider specific offshore requirements.

The most promising locations for offshore wind turbines in the US are off the northeast coast (roughly from Virginia north) and the Great Lakes. Desired site characteristics are a good wind resource, shallow water (less than 30 m), and proximity to land, load centers, and onshore transmission lines. In many respects, potential locations are similar to those in Europe. Although hurricanes exist in the US and not in northern Europe, the authors have yet to find compelling proof that the wave conditions differ greatly between the two continents. There are undoubtedly some differing conditions, however. For example, floating ice will exist in the fresh water Great Lakes, whereas in northern Europe ice is found in the more salty Baltic Sea.

3.1. Relation to onshore turbines

Offshore wind turbines are, to date, similar to onshore turbines. It is, therefore, reasonable to expect that the design process for offshore turbines will be similar to onshore turbines. The main differences result from the necessary consideration of additional external conditions. The most obvious difference is the presence of waves, which affect the design of the foundation. Generally, the turbulence intensity is lower offshore, which leads to reduced dynamic turbine loads for isolated turbines (although turbulence within a wind farm may negate this benefit). Floating ice may also affect the design of the support structure.

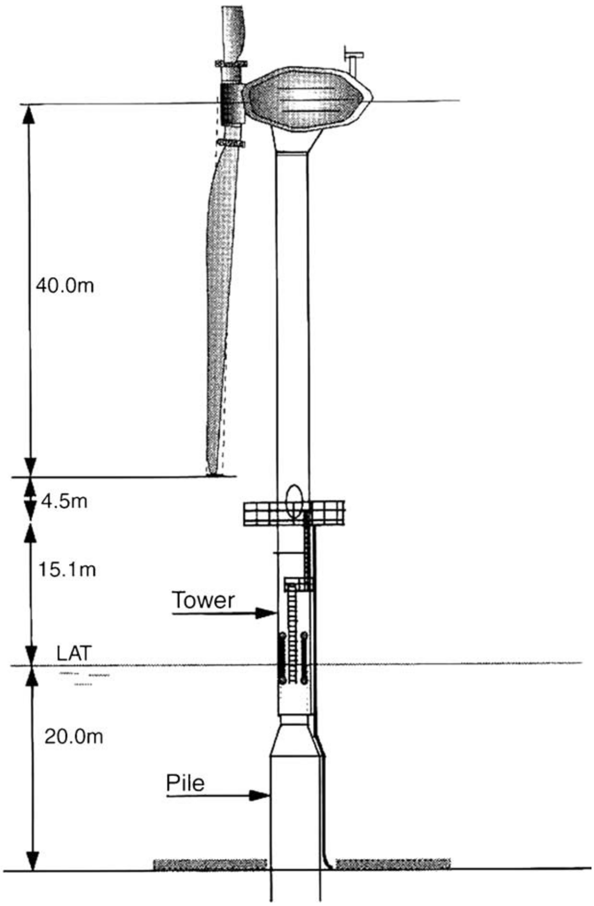

Fig. 1. Schematic of offshore turbine [3].

3.2. Description of external conditions

3.2.1. Wind conditions

For onshore turbines wind is the main source of the primary external conditions. For offshore turbines wind is also quite important although waves are extremely important as well. It is of use to review the characterization of wind, thus, following conventional wind engineering practice [5]; key points of wind characterization are summarized below.

The characterization of wind is strongly related to the physics behind it. In general, wind is created by atmospheric pressure differences due to differential solar heating. Weather fronts are also an important factor. In coastal areas, land and sea breezes can be significant. These factors result in variations in the mean wind over time periods of hours, days, and seasons, a period referred to as the long term. Over the short term, typically defined as 10 min, the wind is affected by turbulent dissipation.

For purpose of design and evaluation of loads, wind is typically considered as being: (1) sustained, (2) a gust, or (3) turbulence. Inputs to simulation models are normally time

series, but they may be derived from spectra. Both wind speed and direction are considered, so, for example, a time series of wind speed for design may involve a distinct change in wind direction over the course of the time period, but may have a more continuous variation in wind speed. As summarized next, for convenience, wind is generally characterized by three main divisions: short term, long term and extreme wind.

3.2.1.1. Short term wind. Short term wind speed is characterized by the mean and standard deviation over a 10 min time interval. Samples on which these measures are based are typically taken at least 1 Hz. The important measures are defined below. The instantaneous wind speed, u, is given by:

$$u = U + \tilde{u} \tag{1}$$

where U is the mean speed and $\tilde{u}$ is the fluctuating component of wind speed.

The mean wind (N_s samples) is:

$$U = \frac{1}{N_s}\sum_{i=1}^{N_s} u_i \tag{2}$$

The standard deviation (sampled) is:

$$\sigma_u = \sqrt{\frac{1}{N_s - 1}\sum_{i=1}^{N_s}(u_i - U)^2} \tag{3}$$

Over short intervals, the distribution (continuous) of wind speeds is approximately normally distributed. That is:

$$p(u) = \frac{1}{\sigma_u\sqrt{2\pi}}\exp\left[-\frac{(u-U)^2}{2\sigma_u^2}\right] \tag{4}$$

Turbulent wind can be thought of as being comprised of sinusoids of various magnitudes and frequencies. These are characterized in terms of the power spectral densities, such as the von Karman spectrum:

$$S_u(f) = \frac{\sigma_u^2 4(L/U)}{[1 + 70.8(fL/U)^2]^{5/6}} \tag{5}$$

or the Kaimal spectrum:

$$S_u(f) = \frac{\sigma_u^2 4(L/U)}{[1 + 6(fL/U)]^{5/3}} \tag{6}$$

The degree to which wind speed at one time is similar to that at another time is characterized by the normalized (i.e., normalized by σ_u^2) autocorrelation function, which in sampled form is

$$R(r\delta t) = \frac{1}{\sigma_u^2(N_s - r)}\sum_{i=1}^{N_s - r} u_i u_{i+r} \tag{7}$$

where r = lag number and δt = the sampling interval.

3.2.1.2. Long term wind. Long term wind conditions are typically characterized in terms of the long term mean, $\bar{U}$, and long term standard deviation, σ_U

$$\bar{U} = \frac{1}{N}\sum_{i=1}^{N} U_i \tag{8}$$

where N is the number of long term data points

$$\sigma_U = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(U_i - \bar{U})^2} \tag{9}$$

The long term probability density functions (pdfs) commonly used are the Rayleigh and the Weibull. The Rayleigh pdf is:

$$p(U) = \frac{\pi}{2}\left(\frac{U}{\bar{U}^2}\right)\exp\left[-\frac{\pi}{4}\left(\frac{U}{\bar{U}^2}\right)^2\right] \tag{10}$$

Expressed as a cumulative density function, the Rayleigh function is

$$F(U) = 1 - \exp\left[-\frac{\pi}{4}\left(\frac{U}{\bar{U}^2}\right)^2\right] \tag{11}$$

where $F(U)$ denotes the probability that the wind speed is less than or equal to U.

The Weibull pdf is:

$$p(U) = \left(\frac{k}{c}\right)\left(\frac{U}{c}\right)^{k-1}\exp\left[-\left(\frac{U}{c}\right)^k\right] \tag{12}$$

Expressed as a cumulative density function, the Weibull function is

$$F(U) = 1 - \exp\left[-\left(\frac{U}{c}\right)^k\right] \tag{13}$$

where c is the scale factor and k is the shape factor.

3.2.1.3. Extreme winds. For extreme design conditions, gusts (on the order of seconds) are typically predicted from somewhat longer term periods (on the order of minutes) measured by use of gust factors [3]. The gust factor, u', is determined by:

$$u' = 0.42\ln(T_1/T_2) \tag{14}$$

where T_1 is the averaging period of the mean wind speed (10 min to 1 h) and T_2 is the gust averaging period (3 s to 1 min).

The wind speed over a shorter time can be expressed by

$$u = (u' I_{\mathrm{t}} + 1)U \tag{15}$$

where I_{t} is the turbulence intensity, given by

$$I_{\mathrm{t}} = \sigma_u/U \tag{16}$$

As defined by IEC 61400-1 [6], an extreme wind speed is the expected value of the highest wind speed, averaged over time t seconds with an annual probability of exceedance of $1/N$,

where N is the recurrence period in years. In the IEC standards, time intervals corresponding to a short-term averaging interval of 10 min and gusts of 3 s are used. One approach to the estimation of extreme winds is as follows. The 10 min extreme wind is defined by a factor multiplied by the reference wind for the site (adjusted for height). The extreme gust is defined in terms of the 10 min extreme wind. Other methods used, in particular when limited data are available, include the use of the Gumbel or reverse Weibull distributions (see for example, [3] or [7]).

3.2.2. *Wave conditions*

The mathematical analysis of ocean waves (see Stewart [8]) is similar to that of turbulent wind. This is no coincidence, since both turbulent wind and ocean waves are often modeled as the linear combination of sinusoidal variations over a range of frequencies and with random phase. The fundamental differences between how wind and ocean waves are viewed are: (1) with wind the important parameter is wind speed (m/s), whereas with ocean waves it is wave height (m) and period (s) and, (2) wind speed is typically viewed primarily in the time domain and secondarily in the frequency domain, whereas ocean waves are viewed primarily the other way around.

3.2.2.1. Wave behavior. Wave motion is quite mathematically complicated. Sometimes it can be modeled by sinusoids, which can occur either singly or in linear combinations. Other times, wave behavior is highly non-linear, such as in shallow water and when they are breaking. Fortunately, many of the most important features of waves can be captured by the relatively simple Airy model. This model is of particular interest since it is generally applicable to sinusoidal waves as well as linear combinations of sine waves. In addition, it provides insight into behavior of other waves, such as non-linear and shallow water waves. All variables of interest, such as the wave amplitude, $\hat{H}$, can be derived from the velocity potential $\Phi(x,y,z;t)$, which is given by [9]:

$$\Phi(x,y,z;t) = \frac{\hat{H}g}{\omega} D(z)\sin(ks - \omega t) \tag{17}$$

The water particles travel in circular trajectories, with radius r decreasing with water depth:

$$r = \hat{H}\exp(kz) \tag{18}$$

The magnitudes of the particle velocity and acceleration are given by:

$$u = \hat{H}\omega\exp(kz) \tag{19}$$

As the wave advances, the particle velocity is in the direction of wave propagation at the crest of the wave, and in the opposite direction at the trough. These velocities decrease with depth, until at a depth of $kz < -3$ the water is nearly undisturbed by the wave. These relations reflect an important observation: wave characteristics are significantly affected by water depth. The Airy model also gives simple relations for wave length and wave period and for the forward propagation velocity of the wave, which is known as the celerity.

The Airy model can often be used directly, especially in deeper water and when the waves are not excessively large. In other cases, other models must be used, such as the non-linear Stokes model or stream functions. Fig. 2 [9] shows which models can be used, depending on water depth and wave height. See Ochi [10] for additional details on waves.

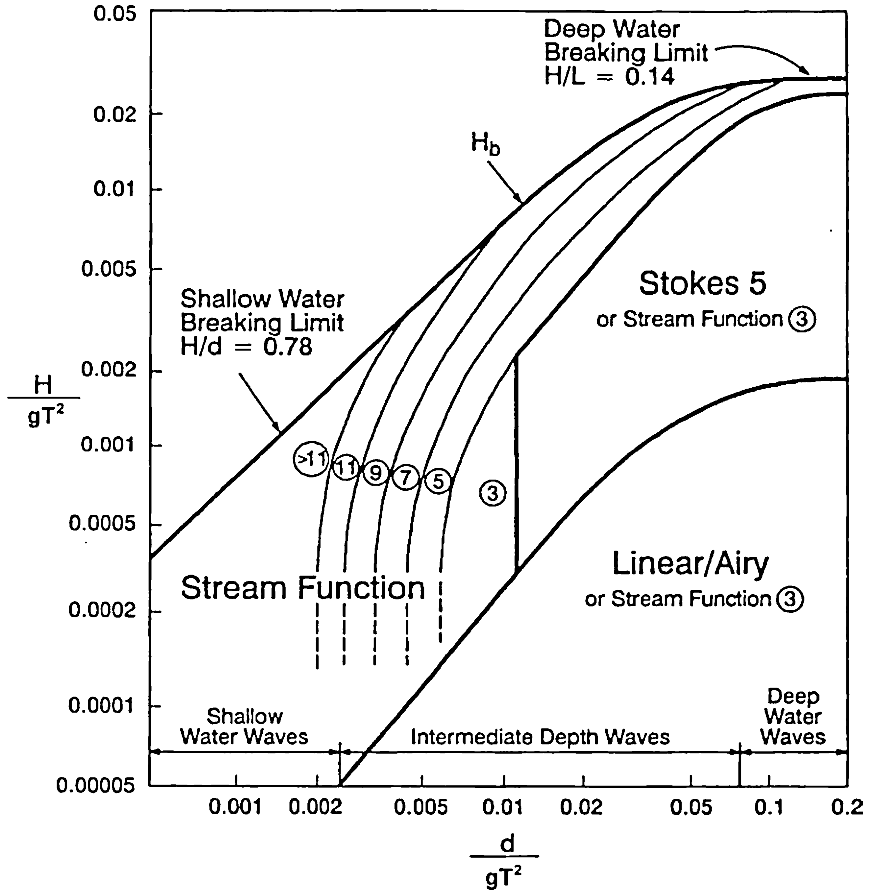

Fig. 2. Applicability of wave models [9].

3.2.2.2. Short term waves. Where ocean waves are concerned, the short term or 'sea state' refers to time periods of less than three hours. Within such time periods, the most important parameter is the significant wave height, H_s. The second most important parameter is some measure of the characteristic frequency (or, equivalently, time period). Next on the list of importance is the power spectral density (psd) of the waves, $S(f)$. Analogously to wind speed psd's the wave psd describes the amount of energy in sinusoidal waves of various frequencies. Historically, significant wave height was determined visually: the average of the largest one third of the waves. Generally, H_s is computed from the standard deviation, σ_H, of the wave height. In practice, H_s is sometimes defined as $4\sigma_H$. The standard deviation is in turn found in the frequency domain from the integral of the psd rather than from the time series. Thus:

$$H_s = 4\sigma_H = 4\sqrt{\int_0^\infty S_H(f)\mathrm{d}f} \tag{21}$$

Several measures of the wave period are used. Two commonly used periods are the peak period, T_p, and the mean (or zero-crossing) period, T_z. T_p is the reciprocal of the peak frequency, f_p, at which the psd has its greatest value. The zero-crossing period, T_z, is found from the spectrum as follows [11]:

$$T_z = \sqrt{\int_0^\infty S_H(f)\mathrm{d}f \Big/ \int_0^\infty f^2 S_H(f)\mathrm{d}f} \tag{22}$$

There are two models in common use for wave spectra: the Pierson–Moskowitz (PM) and JONSWAP [8]. The PM spectrum is well suited for fully developed seas. The JONSWAP spectrum is a modified PM spectrum and is applied to fetch-limited seas—areas in which waves are not fully developed. Waves in such conditions have frequencies more narrowly concentrated around a central frequency.

The PM spectrum is defined by [10]

$$S_{PM}(f) = A\mathrm{e}^{-B/f^4}/f^5 \tag{23}$$

where $A = (5/16)H_S^2 f_p^4$ and $B = 5f_p^4/4$.

The JONSWAP spectrum is defined by [10]

$$S_{JS}(f) = CS_{PM}\gamma^{\exp\{-(f-f_p)^2/2(\sigma f_p)^2\}} \tag{24}$$

where $\gamma^{\exp\{\cdots\}}$ is a 'peak enhancement factor', σ is a numerical parameter, and C is a normalizing constant.

The two spectra are shown in Fig. 3 where they have been normalized by dividing each spectrum by its variance. This figure also shows two common turbulent wind spectra, the von Karman and the Kaimal (with an integral time scale of 30 s) for comparison. It can be noted that the wave spectra cover a much narrower frequency range than do the wind spectra.

Over a short term interval, such as an hour, there are numerous waves. The relative number of occurrences of waves of various heights, H, over that interval can be described by the Rayleigh cumulative density function:

$$F(H) = 1 - \exp\left[-2\left(H/H_s\right)^2\right] \tag{25}$$

The distribution of wave periods is approximately Gaussian.

3.2.2.3. Directionality. The discussion above has not considered direction. Wave direction is often of interest in designing offshore wind turbines, especially in so far as it differs from wind direction. When direction is considered the spectrum is written as

$$E(f,\theta) = S(f)D(\theta,f) \tag{26}$$

where $D(\theta,f)$ is the directional distribution. $D(\theta,f)$ may be thought of as the distribution of wave energy of various frequencies over the direction. The distribution will thus reflect the observation that waves from a number of sources and directions can exist at the same time. The two parameter spectrum $D(\theta,f)$ is usually not available, so a one parameter spectrum, $D(\theta)$, is used instead. More information on the subject of directional spectra can be found in Krogstad and Arntsen [11].

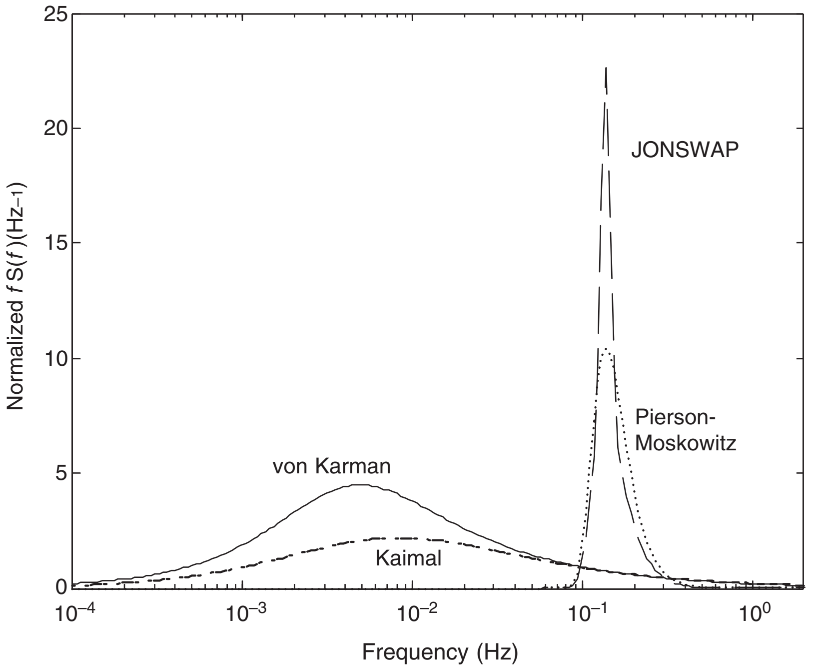

Fig. 3. Normalized wind and wave spectra, $L/U = 30\,\mathrm{s}$.

3.2.2.4. Long term waves. The long term wave climate (a collection of many sea states) is typically described by a distribution function of mean significant wave height, H. The Weibull distribution function is commonly used. Thus

$$F(H) = 1 - \exp\left(-\left(\frac{H - H_0}{H_c - H_0}\right)^{\gamma}\right) \tag{27}$$

where H_c, and γ are analogous to the scale parameter c and shape parameter k used in Weibull modeling of wind speed. H_0 is often taken to be equal to zero.

3.2.2.5. Extreme waves. There are two items of interest with respect to extreme waves: (1) the largest wave within a particular sea state (class of occurrences of significant wave height and mean period), and (2) the largest wave over a number of sea states (corresponding to one or more years, for example).

Based on probability theory for stochastic variables, it can be shown that the largest of N waves within a particular sea state have the following cumulative distribution function [11]:

$$P(H_{\max} < h) = \left[1 - \exp\left(-2\left(h/H_{\mathrm{S}}\right)^2\right)\right]^N \tag{28}$$

For multiple sea states over a number of years the following applies

$$P(H_{\max} < h) = \Pi_{ij}\left[1 - \exp\left(-2\left(h/H_{\mathrm{S}_{ij}}\right)^2\right)\right]^{\alpha_{ij}/T_{zij}} \tag{29}$$

where the subscript ij refers to particular sea state. If the total time is A, and the fraction of the time the sea state is p_{ij}, then the time a_{ij} in that sea state is A p_{ij} so the number of waves in that sea state is a_{ij}/Tz_{ij}. The expression Π_{ij} indicates that a product is to be taken over all sea states.

The magnitude of extreme waves depends on a multitude of factors, including water depth, distance from shore, fetch, and overall climate conditions. Location is also a significant factor, as shown by the map of estimated extreme waves in Fig. 4 [12]. An example of a large design wave is the 29.3 m wave used at an oil platform off the coast of Newfoundland [13].

3.2.2.6. Extreme waves and wind. In the design of offshore wind turbines, a primary consideration is the combined effect of the wind and the waves. It is likely to be the case the high winds are accompanied by large waves, but not necessarily that extreme winds are accompanied by extreme waves at precisely the same time. The question then arises how to choose suitable combinations of wind and waves that will result in loads with specified return times. One approach is to consider extreme winds, combined with a large, but not extreme wave, and vice versa. Another approach is to predict loads using a range of wind and waves, and derive joint probability estimates that will allow prediction of loads with particular return times. This approach is described by Cheng [3].

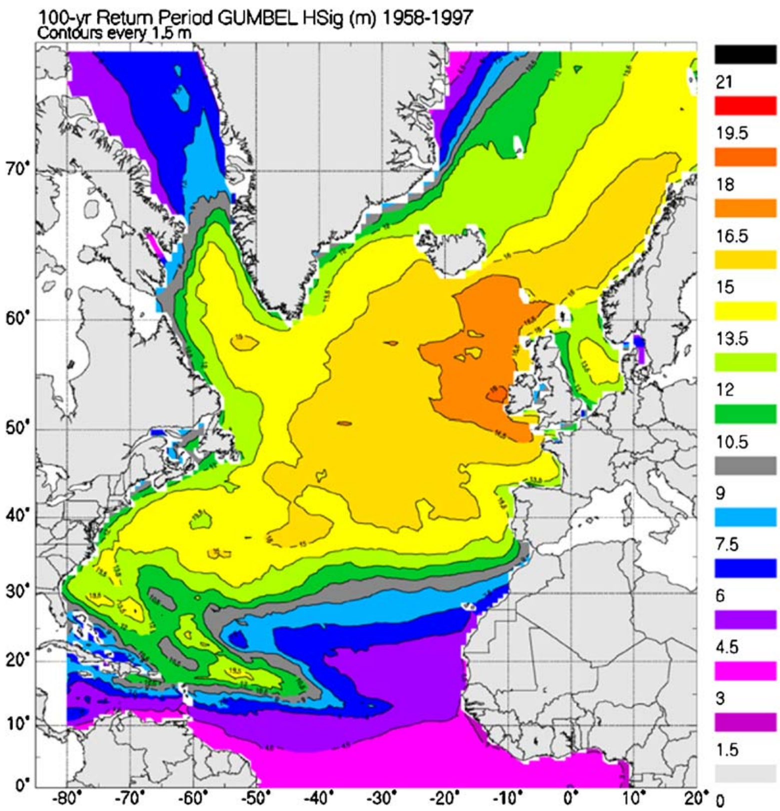

Fig. 4. Map of 100 year return extreme H_s 1956–1997 [12].

3.3. Load estimations

3.3.1. Wind loads

Wind induced loads on a wind turbine have been thoroughly discussed elsewhere [5] and will only be summarized briefly here. In essence, the wind acts through lift or drag forces on various parts of the turbine. Given the geometry of the structure, the cumulative effect of those forces results in the loads of interest. The loads are typically calculated with detailed simulation models, such as BLADED [14], FAST [15], FLEX5 [16], or ADAMS [17]. The International Electrotechnical Commission Safety Design Standards [2] provide guidance on the use of external conditions as inputs to those models.

3.3.2. Wave loads

Wave loads are less well known in the wind industry. While they will only be summarized here, more details can be found elsewhere [9,10]. The fundamental equation used in estimating wave loads is the Morison equation. It consists of an inertial component (associated with the acceleration of the water) and a drag component (associated with the velocity of the water). On a cylinder, for example [9],

$$\tilde{F} = C_{\mathrm{M}} \frac{\rho_{\mathrm{w}} \pi D^2}{4} \dot{u} + C_D \frac{\rho_{\mathrm{w}} D}{2} |u| u \tag{30}$$

3.3.3. Wind and wave loads

Extreme wind and wave loads are sometimes assumed to occur simultaneously, but this assumption gives a conservative estimation of the extreme load. More often, there is a time lag between the two maxima. Cheng [3] examined models with small time lags and found this lag to be between 0 and 20 s. The proper determination of extreme loads from the combination of wind and wave loads, however, is not well understood and further investigation is required.

3.3.4. Ice loads

A third external condition affecting offshore turbine design is floating sea and lake ice. Ice charts indicate that floating ice has been observed in bays along the northeastern US and Alaskan coasts and in the Great Lakes. It is likely, therefore, that turbines installed in these locations will be subjected to ice-induced tower loading. Both horizontal and vertical forces will be exerted on a tower by floating ice. Horizontal forces arise from moving ice, temperature changes in a rigid ice cover, water level changes below rigid ice, and pressure from packed ice. Vertical forces are due to water level changes beneath a rigid ice cover [18].

Several measures have been suggested and employed to reduce the harmful effects of these forces. Holttinen et al. [19] suggest not installing turbines in water where the ice grows to a thickness greater than 0.4 m, thereby limiting the ice loads to 1 MN. Ice cones installed at the water line can weaken and break moving ice (as employed at the Middelgrunden wind farm off of Copenhagen, Denmark). The US Army Corps of Engineers (USACE) [20] recommends the use of bubblers to thin and weaken the ice near harbor piers and pilings or coating structures with a slippery material to reduce the foundation adherence. Protective piles may be needed to shield turbines from the brunt of

the horizontal forces. Vibration reduction techniques may also be needed to damp oscillations in the nacelle.

When considering sea ice, the primary parameters used to characterize tower loading are ice thickness, density, crush strength, spatial extent (from an ice atlas), water level change, and water depth. For further discussion of ice engineering and design, see [21].

4. Offshore data sources in the US

4.1. Buoy data

The National Oceanic and Atmospheric Administration (NOAA) operates several hundred meteorological stations in the US coastal waters and Great Lakes [22]. While the complete list of stations would be too long to list here, the stations in the Northeast and Great Lakes are listed in Table 1 as an example of the quantity of data available. All of the offshore meteorological stations listed in Table 1 record a standard set of meteorological measurements. The measurements relevant to offshore turbine design include air and sea

Table 1
Active offshore met stations operated by NOAA in the Northeastern (NE) and Great Lakes (GL) regions

Station*	Region	Met data start data	Depth (m)	Spectral data start year
44004	NE	1977	3163.8	1996
44005	NE	1978	21.9	1996
44007	NE	1982	18.9	1996
44008	NE	1982	62.5	1996
44011	NE	1984	88.4	1996
44013	NE	1984	55.0	1996
44017	NE	2002	52.4	2002
44018	NE	2002	56.7	2002
44025	NE	1975	40.0	1996
44027	NE	2003	182.0	2003
BUZM3	NE	1985	–	1997
IOSN3	NE	1984	–	–
45001	GL	1979	250.3	1996
45002	GL	1979	174.4	1996
45003	GL	1980	146.3	1996
45004	GL	1980	218.5	1996
45005	GL	1980	14.6	1996
45006	GL	1981	161.5	1996
45007	GL	1981	164.4	1996
45008	GL	1981	62.5	1996
45012	GL	2002	145.0	2002
DBLN6	GL	1983	–	–
DISW3	GL	1983	–	–
LSCM4	GL	2001	–	–
PILM4	GL	1984	–	–
ROAM4	GL	1983	–	–
SBIO1	GL	1983	–	–
SGNW3	GL	1983	–	–
STDM4	GL	1984	–	–

*Numbered stations are moored buoys.

surface temperatures; sea level barometric pressure; wind speed, direction, and gust speed; significant wave height; and average and dominant wave periods. Most stations also record more detailed spectral information, including binned spectral wave densities. These and the standard meteorological data are recorded once per hour and are available as time series.

4.2. Voluntary observation ship data

NOAA coordinates the data from the Voluntary Observation Ship (VOS) program [22]. Observations made on ships at sea are tabulated and transmitted to land in near real-time. Started in the 1850s, the VOS program currently includes participants from 49 countries. In the US, more than 1600 ships contribute to the program every year. Measurements included are similar to the standard meteorological measurements collected by NOAA buoys.

While the VOS program allows for data collection in areas where there are no buoys, there are limitations to the data gathered by ships in the VOS program. The points of observation are moving and so long-term data for a given location do not exist. Also, data gathered over time in a particular area have been gathered by several different people on different ships, introducing measurement inconsistencies.

4.3. Comprehensive ocean atmosphere data set

Using data from its buoys and VOS program, NOAA also administers the Comprehensive Ocean Atmosphere Data Set (COADS). COADS data are binned into squares of either 1 or 2° of latitude/longitude on a side. Monthly statistical summaries are currently available for each square from 1854 to 1995. NOAA plans to release subsequent data when they are have completed their quality control process. Available data include sea and air temperatures, scalar and vector wind information, and sea level pressure [23]. COADS can be viewed as an attempt to average out the limitations of the VOS data.

4.4. Ice data

US ice data are publicly available from the National Ice Center (NATICE, part of NOAA), the National Snow and Ice Data Center (NSIDC), and the National Data Buoy Center (NDBC, part of NOAA). Ice charts are publicly available for the eastern coast of Canada, Hudson Bay, Alaska, and the Great Lakes. Floating sea ice has been observed in bays and inlets along the northeastern coast of the US and the western coast of Canada, but such occurrences are rare. No public charts or data were found for these locations. Coastal locations south of those listed above are not affected.

5. Estimates of offshore data

It is seldom the case that measured meteorological data are available for a prospective offshore wind farm. It is, therefore, necessary to estimate such data from the best source available. There are two main possibilities. The first, and most common, is to make use of hindcast databases. The second is to take short term data at the site and correlate it with longer term data from the general vicinity. Measure-correlate-predict (MCP) techniques

are well established for wind speed and it is proposed below that they could be used for wave estimates as well.

5.1. Hindcast techniques

Hindcast is the name given to techniques used for estimating various meteorological parameters for weather, which have occurred in the past. The estimates are made by using other data that is more readily available. Hindcasts are most often undertaken to produce wave data, since measurement of waves is expensive and wave data are often not available. The output of hindcast models is normally in time series form and includes at least H_s and f_p. Hindcast output often includes wave direction and wave spectral information. Subsequent analysis is often applied to the hindcast output to estimate extreme significant wave heights or extreme wave heights. These estimates are of use in designing offshore structures. The output of hindcast models is stored in databases, many of which are readily available. For example, the output of the USACE Wave Information System (WIS) is particularly useful [24]. Two other hindcast studies of interest include the NESS/NEXT study of the North Sea and the 40 year AES40 study of the North Atlantic [25].

Hindcast estimates are produced by mathematical computer models, which are tuned using measured data. The primary steps involved include: (1) estimation of wind speed and direction using atmospheric pressure data as input to weather models and (2) use of the estimated wind speed, in conjunction with various oceanographic information, to estimate the sea state. The area of interest is divided into grids, and calculations are done for each grid intersection point. Prediction of wave characteristics from the wind speed is based on the 'transport equation'. The latter can be expressed in a variety of forms with varying degrees of complexity. One of the simplest [26] is the following:

$$\frac{\partial E^{2/3}}{\partial t} + A(u^{*})E^{2/3}V_{\mathrm{g}}\nabla(E^{2/3}) = S \tag{31}$$

where E = spectrally integrated energy of the waves, $A(u^*)$ = a function of u^* (the friction velocity), V_g = unit vector in the direction of the wave group velocity, S = source function.

The source function depends primarily on wind speed, and includes the wind input itself, as well as effects related to the non-linear wind to wave interaction, dissipation due to breaking waves, and bottom friction. Note that as expressed in Eq. (31), $E^{2/3}$ represents momentum. Thus, S represents the fraction of momentum transferred from the wind to the sea surface.

The accuracy of hindcasts has been a subject of some discussion. Liu et al. [27] point out that errors in wind speed predictions, which can be significant, can lead to even greater errors in wave estimates. Second, even when real wind data are used as input to hindcast wave estimates, there can be significant errors in the results [28]. These results suggest that there may be limitations to the fundamental models underlying the hindcast methods.

5.2. Measure-correlate-predict techniques

5.2.1. Offshore wind

Measure-correlate-predict (MCP) algorithms are used to predict the wind resource at target sites for wind power development. MCP methods determine a relationship—typically based on 8–12 months of concurrent data—between the target and reference sites.

This relationship is then used with long-term data from the reference site to predict the mean wind speed, wind speed distribution, and direction distribution at the target site. Often the data are binned by direction sector and separate relationships are determined for each sector. Numerous variations on MCP models and algorithms have been proposed (see Rogers et al. [29]).

The accuracy of the predictions between sites on land is known to be affected by a variety of factors, such as stochastic variations in wind speed and direction over time and distance, time of flight delays, large-scale and small-scale weather patterns, and atmospheric stability. In addition to these factors, offshore predictions could be affected by water temperature, (resulting in changes in stability), and a varying roughness length (a function of wind speed), fetch and wind-wave dynamics, [30].

Each of the variables mentioned above affects the cross-correlation between the wind at the reference and targets sites. In general, the greater the cross-correlation between the two sites, the less uncertain the MCP results. Recent unpublished research by the authors indicate that cross-correlations between some selected offshore sites were comparable with land based sites, suggesting that the MCP technique is applicable to offshore sites. The accuracy will depend on the two sites that are chosen for the analysis.

5.2.2. Applicability of MCP to waves

The MCP approach may also prove useful for waves. Wave conditions are affected by the same factors that affect wind speeds as well as by fetch, water depth, refraction, reflection, and wave age. Recent unpublished research at the University of Massachusetts has suggested that applying the MCP technique to wave measurements can provide useful information.

An MCP technique that has been shown to provide unbiased estimates (see the variance ratio method described in [29] for specific details) was used to predict H_s and T_z at a buoy (target) in Boston Harbor, designated 44013 (16 NM E of Boston in 55 m deep water). Two different sites were considered as the reference site, 44007, a buoy along the shore (12 NM SE of Portland ME in 19 m deep water) and 44005, a buoy out in the open ocean (78 NME of Portsmouth NH in 22 m deep water). In each case, about 5 years of long term data was available to evaluate the success of the MCP technique. MCP was used to predict the wave heights, periods and wind speeds at 44013. Predictions using 44005 (open ocean) and 44007 (up the coast) were compared.

The mean wind speed over the period of data collection at 44013 was 5.72 m/s. The average of the mean wind speeds predicted using separate sets of a year of data were 5.74 m/s (using 44007) and 5.69 m/s (using 44005). Each of these averages is within 0.5% of the correct value. The standard deviations of the separate predictions using year long data sets were 0.209 and 0.219 m/s. These standard deviations are 3.6 and 3.8% of the mean value.

The average significant wave height for all of the data at 44013 was 0.82 m (the data are shown in Fig. 5). There is significant seasonal variation in significant wave height. For each of the reference sites, the concurrent data covered a slightly different time period, due to gaps in the data. The average of multiple estimates of significant wave height, using separate sets of a year of data (8500 pts), were within 0.2% (using 44007) and 1.14% (using 44005) of the correct value for the respective concurrent data. The respective standard deviations of the estimates were 4.3 and 6.0% of the mean values. Fig. 6 compares the predicted and actual wave height distributions based on one estimate using a year of data from 44005 for the correlation.

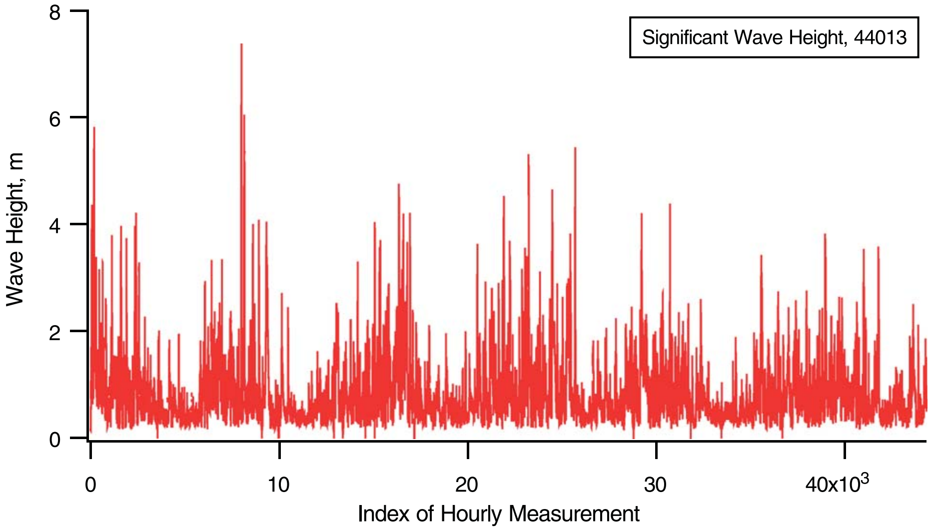

Fig. 5. Significant wave height data for Buoy 44013.

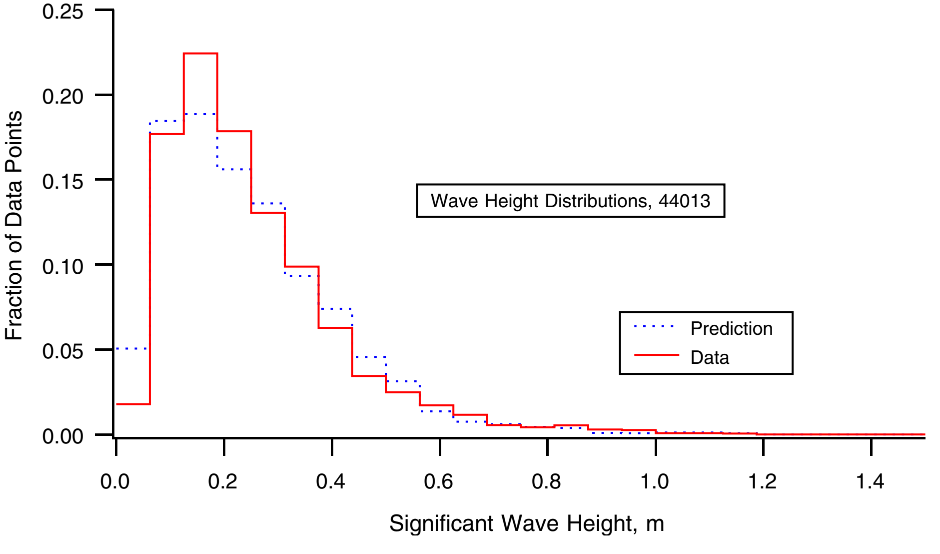

Fig. 6. Predicted and actual wave height distributions.

Tests were performed using smaller lengths of concurrent data for the correlation. The scatter of estimates of overall mean significant wave height did not improve much with more than 7 months of data.

By direction sector, the significant wave height data from the open ocean site and Boston Harbor (44005 and 44013) were fairly well correlated (0.75–0.85) except when the winds were from the W and NW directions. The data from the coastal and Boston Harbor sites

(44007 and 44013) were, in general, well correlated with somewhat lower values from S to NW.

The results indicate that the predicted means and distributions of H_s and T_z are reasonable. In addition, the relative confidence intervals (a measure of the uncertainty) for the wave estimations are found to be on the same order of magnitude as those for the wind speed estimations at the same site: one standard deviation is equal to 4–6% of the estimated value.

The success of this preliminary study suggests that a more in-depth investigation into the applicability of MCP methods to wave data is warranted. Future studies might look into how this technique is best used by the offshore wind industry: whether MCP can be used to estimate extreme events, for example.

6. On-site offshore data collection

6.1. Wind data collection options

A variety of onsite and remote sensing options exist for the measurement of wind at candidate wind farm sites. Issues that drive the design of offshore site-based wind resource measurement systems include the heights at which data are required, the type of data desired, data transmission capabilities, waterproofing of equipment, protection from lighting and corrosion, sea bed properties, and wave and wind loads. Depending on the system and its location, permits may be needed from a variety of federal or local agencies.

Fig. 7 shows a data tower erected by Cape Wind Associates in Nantucket Sound off the coast of Massachusetts in New England [31]. This tower stands 60 m above the mean lower water level and is located approximately 19 km south of Hyannis, MA. The water depth at the tower site is approximately 6.6 m. The installed instrumentation includes cup anemometers at 20, 40 and 60 m above the mean low water level, direction vanes at 20, 38 and 58 m, 3D ultrasonic anemometers at 21, 41 and 60 m, and temperature and barometric pressure sensors at 10 and 55 m (An acoustic Doppler current profiler (ADCP) is installed on the seafloor 90 m from the tower. The ADCP records significant wave height, peak wave period, tide height, water temperature near the seafloor, and ocean current speed and direction). Recent University of Massachusetts work presents an analysis of some of the initial wind data from this site [32].

Rigid support options include monopile platforms, bottom-mounted lattice platforms, bottom mounted guyed towers and jack-up barges. Floating support options include moored discus buoys, discus buoys with tension leg supports, spar buoys and ships. Commercially available measurement options include lattice towers with anemometry and SOnic Detection And Ranging (SODAR) devices. LIght Detection And Ranging (LIDAR) technology is developing rapidly and soon may represent a viable option. Anemometry is the standard approach for wind resource measurements. Anemometers often require backup sensors, data transmission capabilities and periodic maintenance.

SODAR is now beginning to be used for offshore wind resource measurements. It can provide detailed velocity profiles to heights above the rotor without a tower. SODAR measures the amplitude and frequency of acoustic signals reflected from thermal inhomogeneities in the atmosphere. The quality of the data depends on the signal-to-noise ratio of the reflected acoustic pulse. Offshore signal noise may be greater than onshore signal noise due to wind noise in support structures, wave noise, and noise from

Fig. 7. Cape wind data tower (Courtesy Cape Wind Associates).

power systems (diesel generators). Rain also may bias the results. Results of the use of a SODAR at sea showed a significantly smaller number of acceptable data samples than onshore, although this might have been improved with a quieter power source [30].

Remote sensing options include radar systems based on either boats, beaches, planes or satellites. Synthetic Aperture RADAR (SAR) has been used from satellites to estimate offshore wind speeds [33]. Satellite-based SAR images have good coverage (100 km by 100 km) but such systems only collect one image every 10 days and only provide areaaveraged values. Correlations between backscatter coefficient and 10 m wind speeds are used for predicting wind speed. These correlations are based on open sea data. In areas with limited fetch, atmospheric stability, limited wave age, step changes of surface roughness at the land-water location, slicks, tidal currents and water depth may affect the results. Appropriately modified coastal or shipboard radar systems may also be used for wind measurements, but these are not yet commercial products.

6.2. Wave data collection options

Site-based wave measurement options include pressure sensors, resistance-based sensors, capacitance-based sensors, pressure–velocity gauges, two-axis current meters, acoustic

sensors and data buoys. Remote sensing options include stereo photogrammatry,nautical RADAR, altimeters, SAR, and scatterometers [34].

The choice of method depends on cost, observational duration, environmental issues, data acquisition needs, and issues specific to the goals of the measurement campaign. For long-term resource measurements, buoys and stationary equipment are used. They also have the advantage that they can provide not only wave, but also meteorological information. Remote sensing provides wider coverage, but more work needs to be done to provide continuous data.

Analysis of accelerometer data from buoys can be used to determine significant wave height, average period and dominant period and wave spectra (wave energy vs. frequency). Data come ashore either through radio or cell phone communication or via periodic download. Most common data errors result from malfunctions of instruments, errors during data transfer, or data processing software bugs.

Acoustic Doppler current profilers (ADCP) use acoustic signals to detect water motion to characterize currents and wave heights and motion. ADCPs vary in exact capabilities, data handling capacities, data retrieval methods, analysis algorithms, and sensitivities.

Remote sensing of wave fields is most often done with some variations of RADAR. Nautical RADAR have been used with some success to measure wave fields within a few kilometers of the RADAR. Airborne and space-borne RADAR of various kinds are also used. SAR provides a raw resolution of about 25 m with coverage across about 100 km.The data can be analyzed, using models of the physical processes that need to be measured, to determine wave characteristics. The disadvantages of RADAR measurements are the long periods between flights over any given location (which may be on the order of every ten days) and resolution and limited accuracy due to technology issues and analysis models.

Remote sensing systems typically require both the remote sensing system, a land-based data collection site, and a technical support system for analysis of the data [33]. At the moment, a number of the remote sensing approaches, such as those using satellites [8], are still topics of active research.

7. Sources of extreme events

In the Northeastern US, the extreme events of most interest are hurricanes and northeast winter storms. A summary review of each follows.

7.1. Hurricanes

Hurricanes are large, rotating tropical cyclones (also known as typhoons, tropical cyclones, or willy willies). Hurricanes form as well-defined spirals with a distinct lowpressure center (‘eye’) and can grow to 1000 km in diameter. They typically travel with a forward velocity, V_{fm}, of 1–11 m/s. Formed in the tropics, hurricanes impact both the east and west coast of the US [35]. Table 2 gives the 1-minute sustained mean wind speed and the storm surge above the mean sea level for the generally accepted Saffir–Simpson classes of hurricanes [36]. The table also includes the number of hurricanes which made landfall in the US over a 50 year period.

Measured wave data from hurricanes are quite limited and models are often employed to estimate design load parameters, notably H_{s} and T_{p}. Several approaches to determining H_{s} and T_{p} of hurricanes from readily available data have been suggested [37].

Table 2
Saffir–Simpson hurricane classes [31]

Class	Wind speed (m/s)	Storm surge (m)	No. of US hurricanes, 1950–1999
1	32.9–42.6	1.2–1.6	30
2	42.7–49.2	1.7–2.5	15
3	49.3–58.1	2.6–3.8	23
4	58.2–69.2	3.9–5.6	5
5	>69.2	>5.6	2

One interesting characteristic of hurricanes is the presence of an area of extended fetch due to the asymmetry in the wave field relative to the wind field. Hurricanes generate waves, which radiate in a counter-clockwise fashion away from the storm center. To the right of the storm center as viewed from above, the waves move in the same direction as the storm and are, therefore, subjected to the wind for an extended period of time. The result is an area, which has been observed to behave similarly to seas with extended fetch. Some researchers have proposed that an equivalent fetch be determined and that limited fetch modeling schemes, such as JONSWAP, be used to model hurricane spectral behavior [37]. With the equivalent fetch, X, determined from V_{fm}, the radius to maximum wind, R, and the maximum wind velocity, $U_{\max}$, the following relationships for H_{s} and T_{p} are derived:

$$\frac{gH_{\mathrm{s}}}{\mathrm{U}_{\max}^2} = 0.0016\left(\frac{gX}{\mathrm{U}_{\max}^2}\right)^{0.5} \tag{32}$$

$$\frac{gT_{\mathrm{P}}}{2\pi\mathrm{U}_{\max}} = 0.045\left(\frac{gX}{\mathrm{U}_{\max}^2}\right)^{0.33} \tag{33}$$

Usually, R is not measurable during the storm. In the US, R has been found to be, on average, 47 km [38]. This value has been used successfully in simulations when the actual value of R is not known.

Ochi [39] and Young [37] present more in-depth discussions of hurricanes and their impacts on wind and wave conditions, as well as mathematical models of hurricaneinduced sea states.

7.2. Northeast winter storms

Northeast winter storms, or 'nor'easters,' like hurricanes, are cyclones. They differ from hurricanes, however, in that they are usually generated in the winter months and at higher latitudes and have colder air at their core, they do not always form well-defined spirals, and they are often much larger in diameter. Even though these storms produce winds with lower velocities than hurricanes, their increased diameter allows for the development of large and energetic waves. Based on NOAA data [22], it can be seen that approximately 30 nor'easters impact the northern half of the Atlantic coast every year. Due to their frequent occurrences, these storms are likely to play a significant role in the determination of wind turbine design loads.

8. Summary/conclusions

Although no offshore wind turbines have yet been installed in the United States, the experience in Europe over the last decade should be of great help in facilitating the introduction of the technology. In addition to the wind, waves are the other major source of loads which turbines must be designed to withstand. With the offshore turbines constructed so far, the wind effect is limited to the turbine itself and the tower, whereas the waves affect the foundation. In very cold regions, floating ice can result in significant foundation loads as well.

In general, the behavior of waves and their effects on offshore structures are well understood. How the interaction of wind and waves on offshore wind turbines should be accounted for to ensure adequate strength at the minimum cost is still a matter of investigation. Much more study will be needed for designs intended for deeper water.

The United States gathers numerous data which are applicable to the design of offshore wind turbines and wind farms. However, there are still many opportunities to expand offshore data collection and analysis in ways that will aid offshore wind development.

Preliminary investigation has shown that MCP, a standard wind data estimation technique, may be applicable to the prediction of wave data. Further study of these techniques is warranted.

Finally, compared with Europe where all the present offshore turbines are installed, the United States experiences two types of external conditions which may have some impact on turbine design and are worth more detailed study. These are: (1) hurricanes and northeast storms and (2) floating freshwater ice.

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